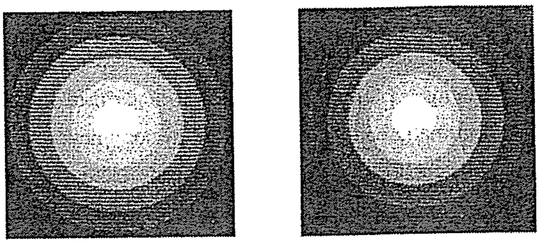


no filter

using a 30 μm molybdenum filter

Fig. 13 Radiograms of concentric-circled steps of 5.0 mm made of PMMA with a maximum height of 25.0 mm.

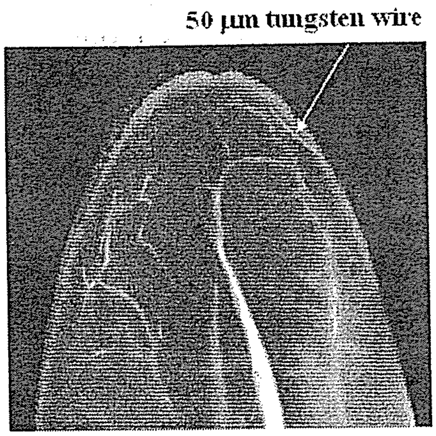


Fig. 14 Angiogram of the external ear of a rabbit.

Table 2 K-series characteristic x-rays of molybdenum.

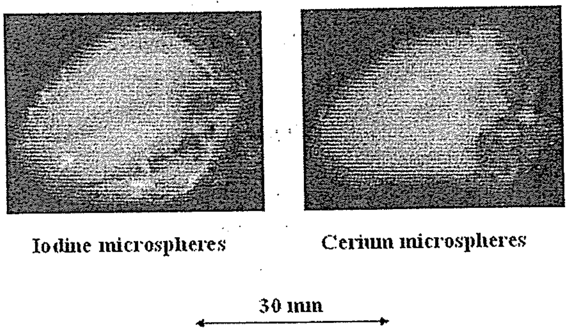
Line	Relative intensity	Photon energy (keV)
$K_{\alpha 1}$	100	17.476
$K_{\alpha 2}$	50	17.371
$K_{\alpha 1,2}$	150	17.441
$K_{\beta 1}$	17	19.605
$K_{\beta 3}$	7	19.587

Table 3 K-series characteristic x-rays of cerium.

Line	Relative intensity	Photon energy (keV)
$K_{\alpha 1}$	100	34.714
$K_{\alpha 2}$	50	34.273
$K_{\alpha 1,2}$	150	34.566
$K_{\beta 1}$	22	39.251
$K_{\beta 3}$	10	39.163

achieved with a copper target (Table 1) with a charging voltage of 50 kV are shown in Figs. 11 and 12. Figure 11 shows radiograms of tungsten wires coiled around pipes made of polymethyl methacrylate (PMMA). The image contrast of a 50 μm-diameter wire around pipe was lower than that of 100 μm wire, and the wires were almost completely visible. Next, the image of water spouted from an injector is shown in Fig. 12. This image was taken using an iodine-based contrast medium added a little. Because the x-ray duration was about 1 μs, the stop-motion image of water could be obtained.

Figures 13 and 14 were obtained by a molybdenum target (Table 2) with a charging voltage of 50 kV and 45 kV, respectively. Figure 13 shows radiograms of concentric-circled steps of 5.0 mm made of PMMA, with a maximum height of 25.0 mm, at a



Iodine microspheres

Cerium microspheres

Fig. 15 Angiograms of extracted rabbit hearts.

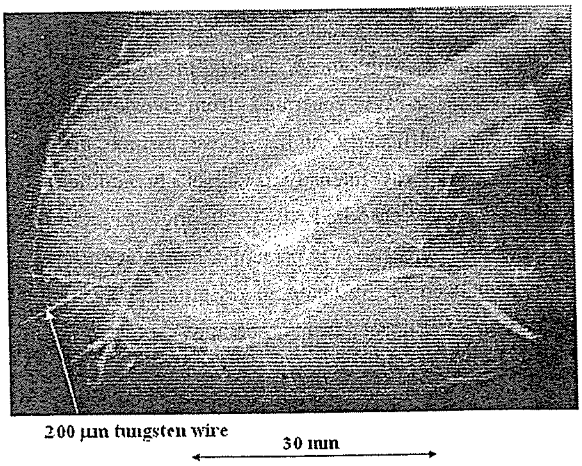


Fig. 16 Angiogram of an extracted dog heart.

charging voltage of 50 kV. In this radiography, we obtained almost identical contrast images, regardless of whether the 30 μm molybdenum filter was employed or not. An angiogram of the external ear of a rabbit is shown in Fig. 14. The angiography was performed using iodine-based microspheres of 20 μm with a charging voltage of 45 kV, and fine blood vessels of about 50 μm are clearly visible.

Angiography using a cerium target (Table 3) at a charging voltage of 55 kV is shown in Figs. 15 and 16. Figure 15 shows angiograms of hearts extracted from rabbits. These two images were obtained using iodine and cerium microspheres, respectively. Where the cerium spheres were employed, the coronary arteries were barely visible, since cerium spheres transmit the cerium characteristic x-rays easily. In angiography of a larger heart extracted from a dog, using iodine spheres, the coronary arteries were clearly visible (Fig. 16).

5. DISCUSSION

Although photon energy of x-ray lasers has been increased in laboratories around the world, it is difficult to oscillate hard x-ray lasers with energies of 10 keV or higher using ordinary methods. Also, sharp soft x-ray lasers have been produced using a gas-discharge capillary [18-20], the signal to noise (SN) ratio having a lower value assuming that the laser intensity is a signal. As compared with these lasers, the SN ratio of characteristic x-rays generated from weakly ionized plasma is significantly higher if we assume that the characteristic x-ray intensity is signal. In addition, K_β rays can be absorbed by filtering to produce monochromatic K_α rays. In principle, in the characteristic x-ray enhancement by spontaneous emission [21] from weakly ionized linear plasma, coherent x-rays are never produced. However, because the characteristic x-rays from plasma are diffused after passing through two slits, this diffusive mechanism must be solved. Recently, several different x-ray lenses have been developed, and a polycapillary plate [22] is quite useful in order to perform parallel radiography and to realize low-priced x-ray systems. Therefore, we plan to perform quasi-monochromatic parallel radiography in conjunction with this generator. In addition, the refractivity of these sharp x-rays, because of diffusive characteristics, is a matter of great interest.

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Quasi-monochromatic x-ray irradiation from weakly ionized linear nickel plasma

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Abstract

In the plasma flash x-ray generator, a high-voltage main condenser of approximately 200 nF is charged up to 50 kV by a power supply, and electric charges in the condenser are discharged to an x-ray tube after triggering the cathode electrode. Flash x rays are then produced. The x-ray tube is a demountable triode connected to a turbo molecular pump with a pressure of approximately 1 mPa. As electrons from the cathode electrode are roughly focused onto a rod nickel target of 3.0 mm in diameter by the electric field in the x-ray tube, a weakly ionized linear plasma consisting of nickel ions and electrons forms by target evaporation. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 17 kA. When the charging voltage was increased, the linear plasma formed, and the intensities of K-series characteristic x rays increased. The K-series lines were quite sharp and intense, and hardly any bremsstrahlung rays were detected. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 30 μC/kg at 1.0 m from the x-ray source at a charging voltage of 50 kV.

Keywords: flash x-ray, weakly ionized linear plasma, K-series characteristic x rays, quasi-monochromatic x rays

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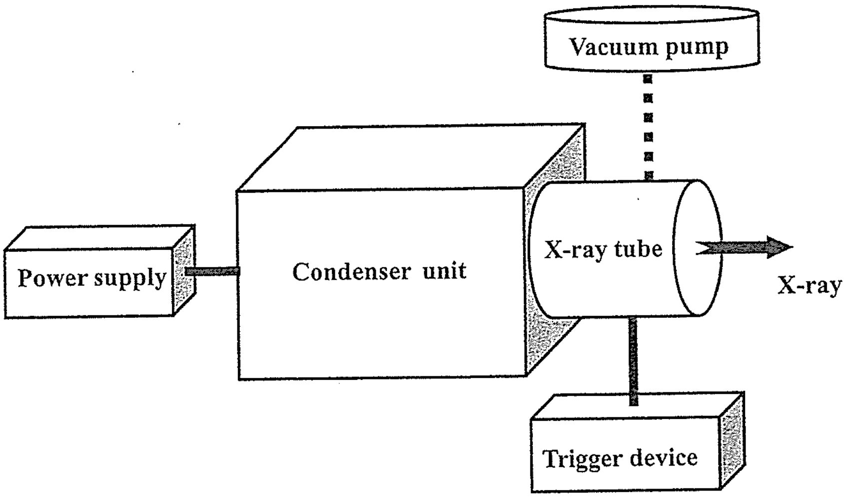

Fig. 1: Block diagram of the high-intensity plasma flash x-ray generator.

1. Introduction

Recently, flash x-ray generators with gas-discharge capillaries have been developed in order to produce soft x-ray laser[1-4] in extremely ultraviolet (XUV) region, and laser energy substantially increased with increases in the capillary length. To be a useful technique for soft biomedical radiography, the photon energy should be increased as much as possible. These kinds of fast discharges can generate hot and dense plasma columns with aspect ratios approaching 1000:1. However, it is difficult to increase the laser photon energy to 10 keV or beyond.

In biomedical radiography, several different flash x-ray generators have been developed corresponding to specific radiographic objectives,[5-7] and high-intensity single generators[8-11] with large capacity condensers were originally developed. Subsequently, repetitive generators[12-16] have been developed, and the repetition rate has been increased to sub-kilohertz using a cold-cathode triode. In addition, the maximum repetition rates were approximately 50 kHz when stroboscopic x-ray generators with hot-cathode tubes is employed.

By forming weakly ionized linear plasma[17-22] using plate and rod targets, we confirmed irradiation of intense K-series characteristic x rays from the plasma axial direction. In these experiments, because we employed a transmission-type x-ray spectrometer utilizing an x-ray film, the relative intensities of the characteristic x rays should be calculated using a digital radiography system.

In this paper, we describe a plasma flash x-ray generator utilizing a rod-target radiation tube, used to perform a preliminary experiment for generating intense and sharp quasi-monochromatic x rays by forming a linear nickel plasma cloud around a fine target.

2. Generator

2.1. High-voltage circuit

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser

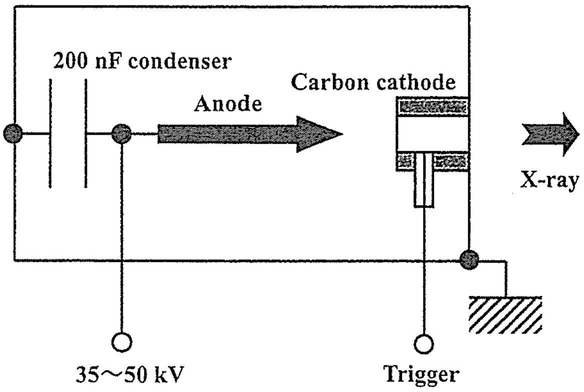

Fig. 2: Circuit diagram of the plasma x-ray generator.

with a capacity of approximately 200 nF, a turbo-molecular vacuum pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line is employed in order to increase maximum tube current. The high-voltage main condenser is charged to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode (Fig. 2). The plasma flash x rays are then produced.

2.2. X-ray tube

The x-ray tube is a demountable cold cathode triode connected to a turbo-molecular pump. The pressure in the tube is approximately 1 mPa (Fig. 3). The tube consists of the following major parts: a hollow cylindrical carbon cathode with a bore diameter of 10.0 mm, a trigger electrode made from copper wire, a stainless steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped nickel target 3.0 mm in diameter with a tip angle of 60°. The distance between the target and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. The electron beam from the cathode electrode is roughly focused onto the target by the electric field in the tube, and evaporation leads to the formation of a weakly ionized linear plasma of nickel ions and electrons around the fine target.

2.3. Principle of characteristic x-ray irradiation

In the linear plasma, bremsstrahlung photons with energies higher than the K-absorption edge are effectively absorbed and are converted into fluorescent x rays (Fig. 4). The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies lower than the K-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the direction opposite that of electron acceleration (Fig. 5), intense characteristic x rays are generated along axial direction of the plasma.

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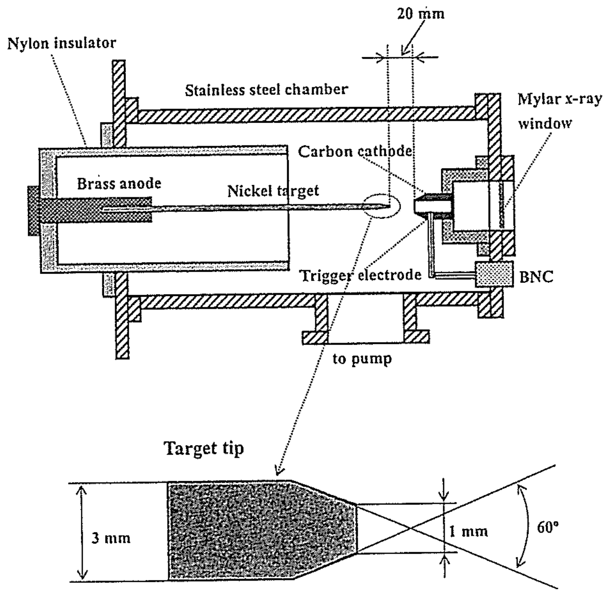


Fig. 3: Schematic drawing of the flash x-ray tube with a rod target.

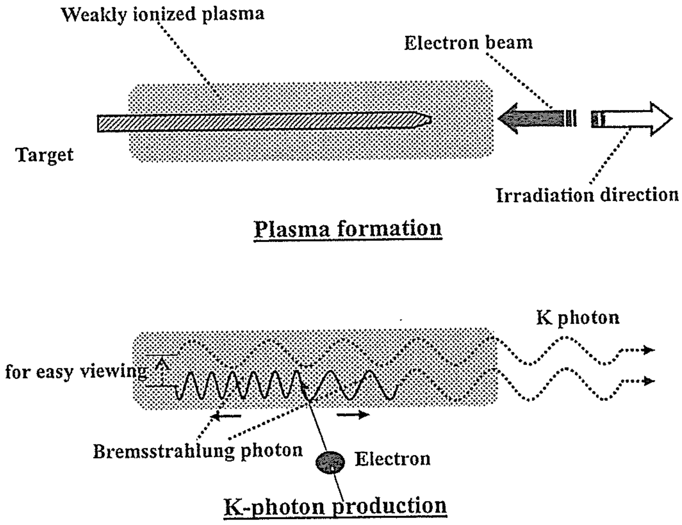


Fig. 4: K-photon irradiation from the plasma.

3. Characteristics

3.1. Tube voltage and current

The tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 6 shows the time relation for the tube voltage and current. At the indicated charging voltages, they displayed damped oscillations. When the charging

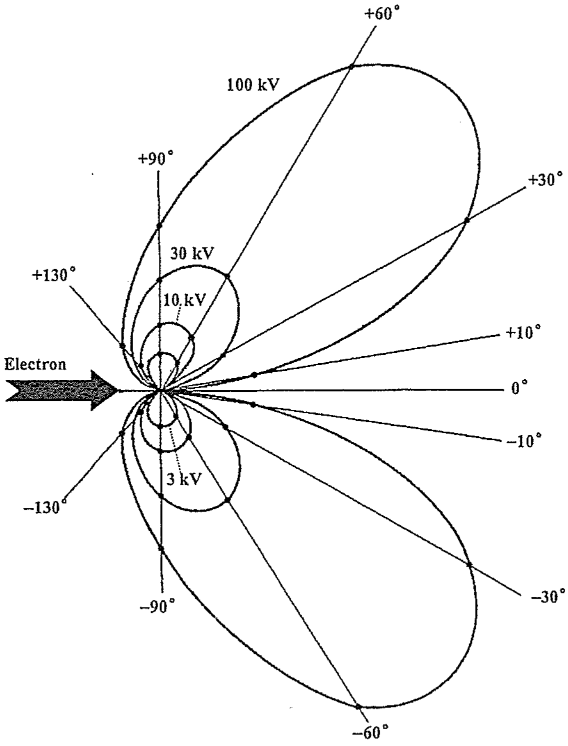
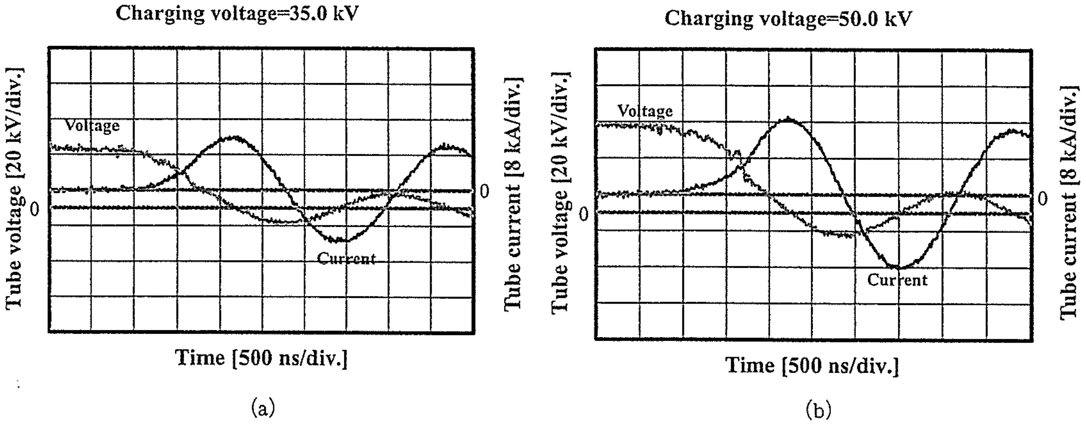


Fig. 5: Bremsstrahlung x-ray distribution with the angle.



(a) (b)

Fig. 6: Tube voltages and currents with a charging voltage of (a) 35.0 kV and (b) 50.0 kV.

voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 17 kA.

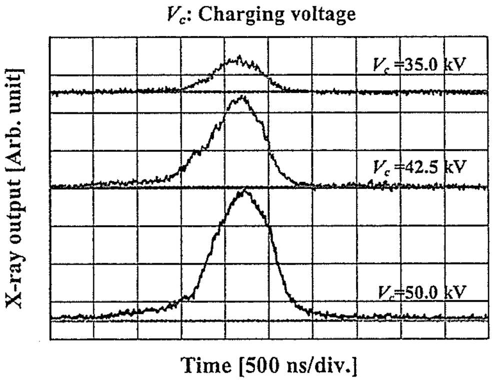


Fig. 7: X-ray outputs measured by a plastic scintillator with changes in the charging voltage.

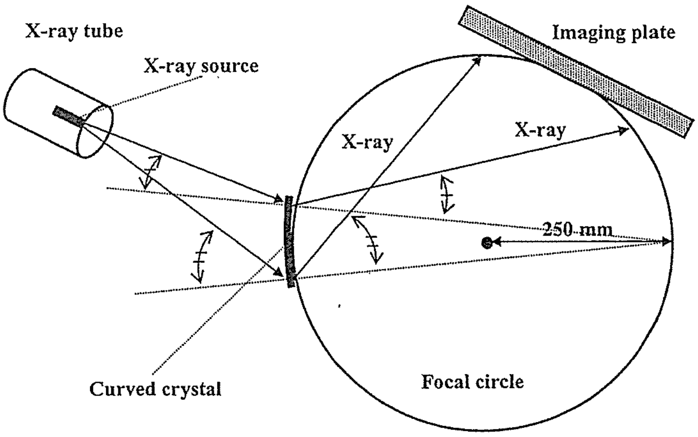


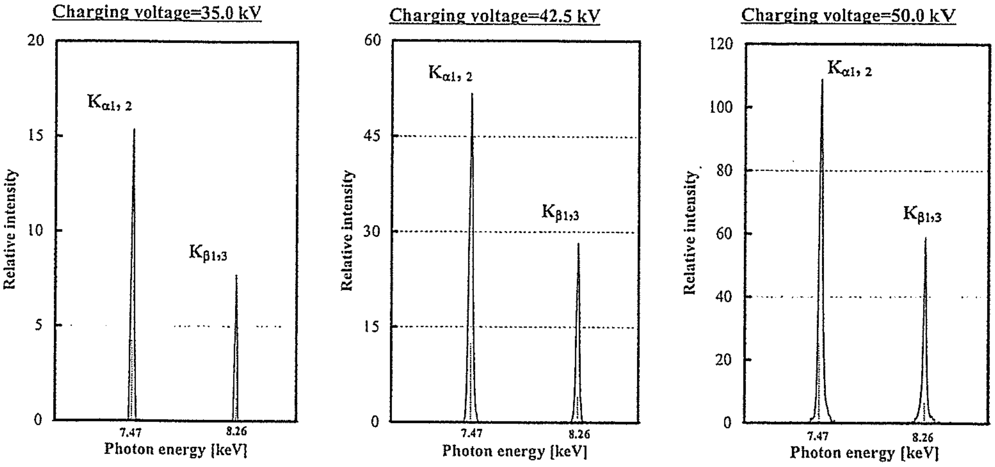
Fig. 8: Transmission-type spectrometer with a lithium fluoride curved crystal and an imaging plate.

3.2. X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 7). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 700 ns; and the time-integrated x-ray intensity per pulse, measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation), had a value of about 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

3.3. X-ray source

The images of the plasma x - ray source were taken using a pinhole camera with a hole diameter of 100 μm. When the charging voltage was increased, the plasma x-ray source grew, and both the beam dimension and the intensity increased.



Charging voltage=50.0 kV

Fig. 9: X-ray spectra from weakly ionized nickel plasma according to changes in the charging voltage.

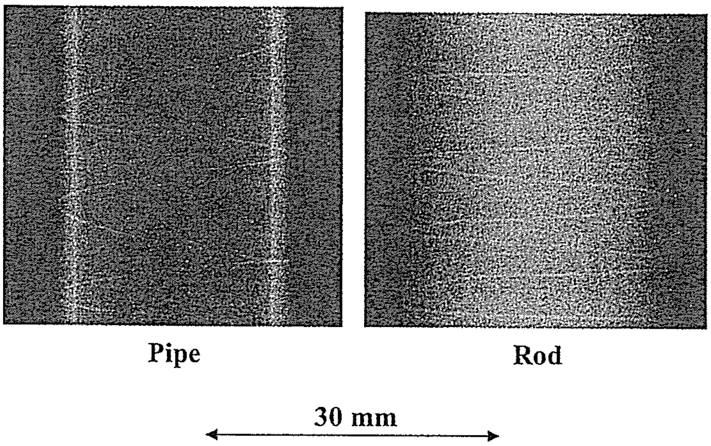


Fig. 10: Radiograms of 50 μm-diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate.

3.4. X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer (Fig. 8) with a lithium fluoride curved crystal of 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system (Konica Regius 150)[23] with a wide dynamic range, and the relative x-ray intensity was calculated from Dicom digital data. Figure 9 shows measured spectra from the nickel target. We observed quite sharp lines of K-series characteristic x rays such as lasers, while bremsstrahlung rays were hardly detected. The characteristic x-ray intensities of K_α and K_β lines substantially increased with corresponding increases in the charging voltage.

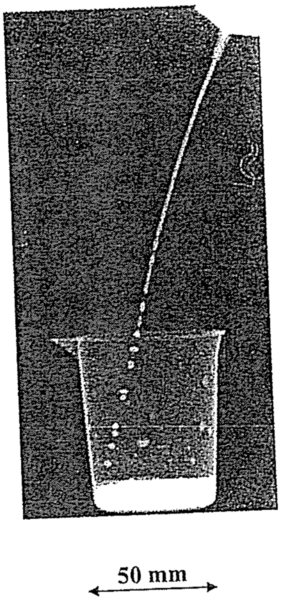


Fig. 11: Radiogram of water droplets falling into a polypropylene beaker from an injector.

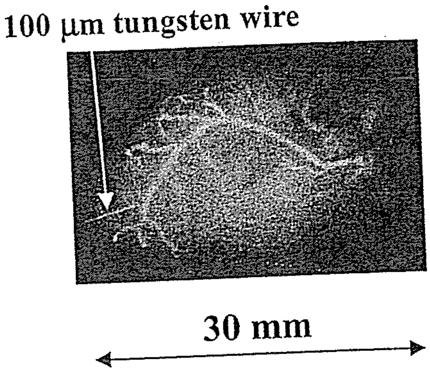


Fig. 12: Angiograms of a rabbit heart.

4. Radiography

Firstly, rough measurements of image resolution were made using wires. Figure 10 shows radiograms of 50 μm-diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate with a charging voltage of 50 kV. Although the image contrast increased using the pipe, 50 μm-diameter wires could be observed.

The image of water droplets falling into a polypropylene beaker from an injector is shown in Fig. 11. This image was taken at a charging voltage of 45 kV, with the slight addition of an iodine-based contrast medium. Because the x-ray duration was about 1 μs, the stop-motion image of water could be obtained.

Figure 12 shows an angiogram of a rabbit heart; iodine-based microspheres of 15 μm in diameter were used with a charging voltage of 50 kV, and fine blood vessels of about 100 μm were visible.

5. Discussion

Concerning the spectrum measurement, we obtained fairly intense and sharp K_α and K_β lines from a weakly ionized linear plasma x-ray source without using the monochromatic filter. Subsequently, the K_β lines can be absorbed easily by a monochromatic cobalt filter.

In medical radiography, because a photon-counting radiography system will be employed, a quasi-monochromatic or monochromatic x-ray generator will be useful to obtain noise-less digital radiograms. In addition, we are designing quasi-monochromatic flash x-ray generator with microsecond x-ray durations utilizing angle dependence of bremsstrahlung x rays.

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography without using a monochromatic filter, and the generator produced number of characteristic photons was approximately 1×10^{14} photons/cm^2 · s at 1.0 m from the source.

In addition, since the photon energy of characteristic x rays can be controlled by changing the target elements, various quasi-monochromatic high-speed radiographies, such as high-contrast micro angiography[23] and parallel radiography[24,25] using an x-ray lens, will be possible.

Acknowledgment

This work was supported by Grants-in-Aid for Scientific Research (12670902, 13470154, and 13877114) and Advanced Medical Scientific Research from MECSST, Grants from Keiryo Research Foundation, JST (Test of Fostering Potential), NEDO, and MHLW (HLSRG, RAMT-nano-001, RHGTEFB-genome-005, and RGCD13C-1).

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REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 74, NUMBER 12 DECEMBER 2003

Quasi-monochromatic flash x-ray generator utilizing weakly ionized linear copper plasma

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In the plasma flash x-ray generator, a 200 nF condenser is charged up to 50 kV by a power supply, and flash x rays are produced by the discharging. The x-ray tube is a demountable triode with a trigger electrode, and the turbomolecular pump evacuates air from the tube with a pressure of approximately 1 mPa. Target evaporation leads to the formation of weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target, and intense characteristic x rays are produced. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 20 kA. When the charging voltage was increased, the linear plasma formed, and the *K*-series characteristic x-ray intensities increased. The *K* lines were quite sharp and intense, and hardly any bremsstrahlung rays were detected at all. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1626007]

I. INTRODUCTION

Flash x-ray generators are very useful in order to perform high-speed radiography, and conventional generators have cold cathode diodes driven by Marx-type high-voltage pulse generators.[1–3] Using the pulse generators, maximum x-ray photon energy has been increased up to about 1 MeV. In addition, an induction linear accelerator with energies of less than 20 MeV has been developed and applied to radiography in detonation.[4,5]

In the photon energy region of lower than 150 keV, because flash x-ray generators can be used to perform soft radiographies including biomedical applications, several different generators[6–9] have been developed corresponding to the radiographic objectives. As compared with the flash x-ray generators, repetition rate can be increased up to the kilohertz range in cases where high-dose-rate stroboscopic x-ray generators[10–12] with hot cathode x-ray tubes are employed.

With recent advances in high-power pulse technology, soft x-ray lasers have been produced by a gas-discharge capillary[13–16] for forming linear plasma, and laser intensity increases with corresponding increases in capillary length. However, it is quite difficult to increase the laser photon energy up to 10 keV or higher by light amplification by stimulated emission of radiation.

In previous research, characteristic x-ray intensities in a thick solid target were increased[17] by the conversion of bremsstrahlung x rays into fluorescent x rays. Subsequently, by forming weakly ionized linear plasma using a plate target,[18,19] irradiation of intense *K*-series characteristic x rays from plasma axial direction was confirmed.

In this article we describe a flash x-ray generator utiliz-

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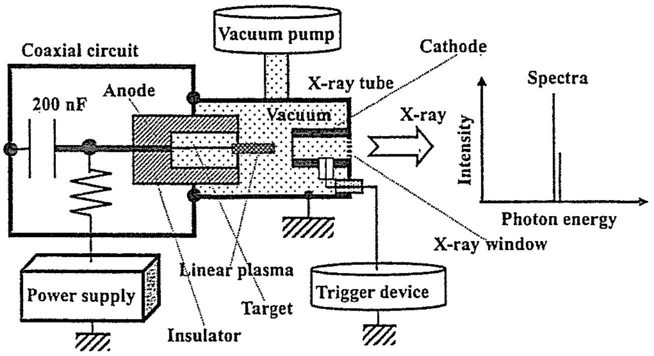

FIG. 1. Block diagram of a high-intensity plasma flash x-ray generator.

ing a rod-target radiation tube, used to perform a tentative experiment for generating higher-intensity quasi-monochromatic x rays by forming a linear copper plasma cloud around a fine target.

II. GENERATOR

A. High-voltage circuit

Figure 1 shows a block diagram of a high-intensity plasma flash x-ray generator. The generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 200 nF, a turbomolecular pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line is employed in order to increase maximum tube current. The high-voltage main condenser is charged up to 50 kV by the power supply, and electric charges in the condenser are discharged to the tube after triggering the cathode electrode with the trigger device. The plasma flash x rays are then produced.

B. X-ray tube

The x-ray tube is a demountable cold cathode triode that is connected to the turbomolecular pump with a pressure of approximately 1 mPa (Fig. 2). This tube consists of the following major parts: a pipe-shaped carbon cathode with a bore diameter of 10.0 mm, a trigger electrode made from copper wire, a stainless-steel vacuum chamber, a nylon insulator, a polyethylene terephthalate (Mylar) x-ray window 0.25 mm in thickness, and a rod-shaped copper target 3.0 mm in diameter. The distance between the anode and cathode electrodes is approximately 20 mm, and the trigger electrode is set in the cathode electrode. As electron beams from the cathode electrode are roughly converged to the target by the electric field in the tube, evaporation leads to the formation of weakly ionized linear plasma, consisting of copper ions and electrons, around the fine target.

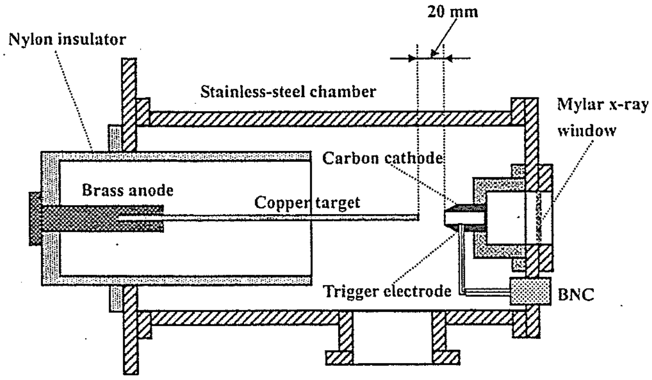

FIG. 2. Schematic drawing of a flash x-ray tube with a rod target.

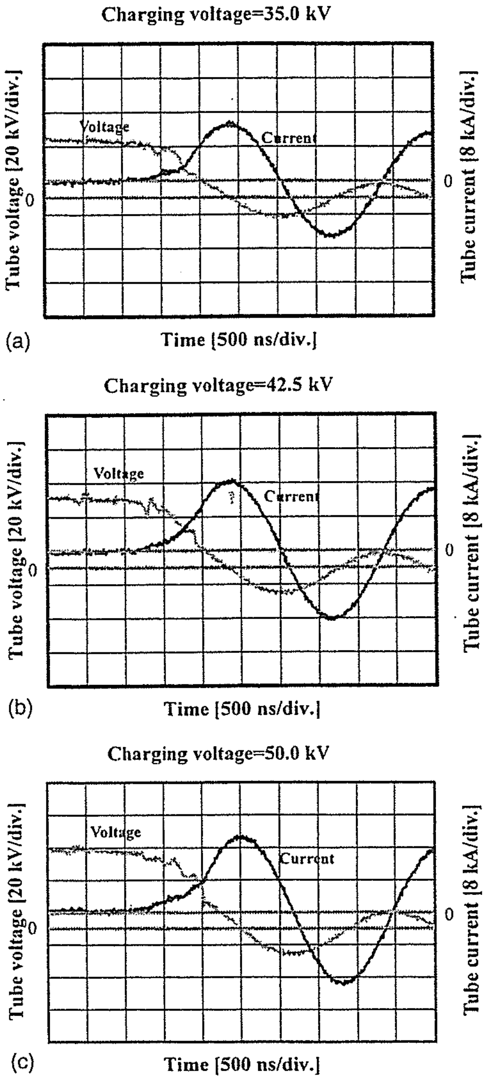

FIG. 3. Tube voltages and currents with a charging voltage of (a) 35.0 kV, (b) 42.5 kV, and (c) 50.0 kV.

C. Principle of characteristic x-ray irradiation

In weakly ionized linear plasma, bremsstrahlung spectra with photon energies of higher than the *K*-absorption edge are effectively absorbed and are converted into fluorescent x rays. The plasma then transmits the fluorescent rays easily, and bremsstrahlung rays with energies of lower than the *K*-edge are also absorbed by the plasma. In addition, because bremsstrahlung rays are not emitted in the direction opposite to electron acceleration, intense characteristic x rays are generated from the plasma-axial direction (refer to Fig. 1).

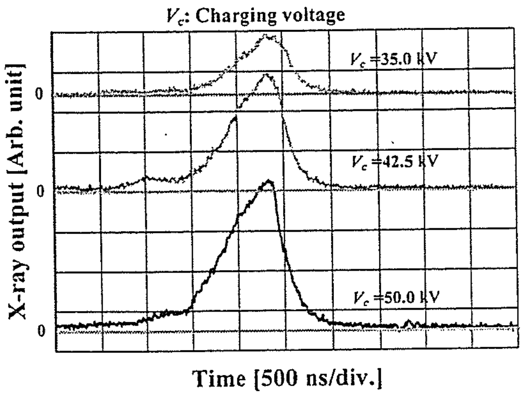

FIG. 4. X-ray outputs at the indicated conditions.

III. CHARACTERISTICS

A. Tube voltage and current

Tube voltage and current were measured by a high-voltage divider with an input impedance of 1 GΩ and a current transformer, respectively. Figure 3 shows the time relation between the tube voltage and current. At the indicated charging voltages, they roughly displayed damped oscillations. When the charging voltage was increased, both the maximum tube voltage and current increased. At a charging voltage of 50 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the maximum tube current was approximately 20 kA.

B. X-ray output

X-ray output pulse was detected using a combination of a plastic scintillator and a photomultiplier (Fig. 4). The x-ray pulse height substantially increased with corresponding increases in the charging voltage. The x-ray pulse widths were about 700 ns, and the time-integrated x-ray intensity measured by a thermoluminescence dosimeter (Kyokko TLD Reader 1500 having MSO-S elements without energy compensation) had a value of about 30 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

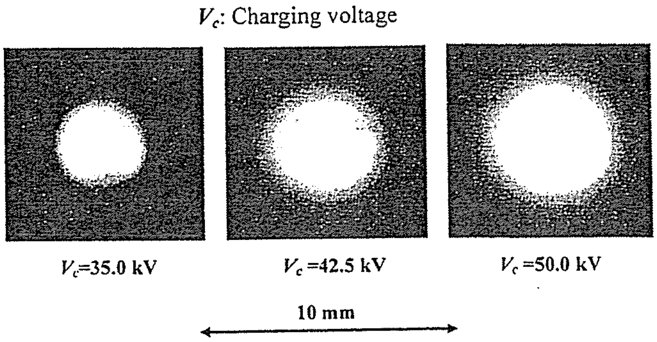

FIG. 5. Images of plasma x-ray source.

C. X-ray source

In order to roughly observe images of the plasma x-ray source in the detector plane, we employed a pinhole camera with a hole diameter of 100 μm (Fig. 5). When the charging voltage was increased, the plasma x-ray source grew, and both spot dimension and intensity increased. Because the x-ray intensity is the highest at the center of the spot, both the dimension and intensity decreased according to both increases in the thickness of a filter for absorbing x rays and decreases in the pinhole diameter.

D. X-ray spectra

X-ray spectra from the plasma source were measured by a transmission-type spectrometer[19] with a lithium fluoride curved crystal 0.5 mm in thickness. The spectra were taken by a computed radiography (CR) system[20] with a wide dynamic range, and relative x-ray intensity was calculated from Dicom digital data. Figure 6 shows measured spectra from the copper target. In fact, we observed quite sharp lines of K-series characteristic x rays such as lasers, while brems-

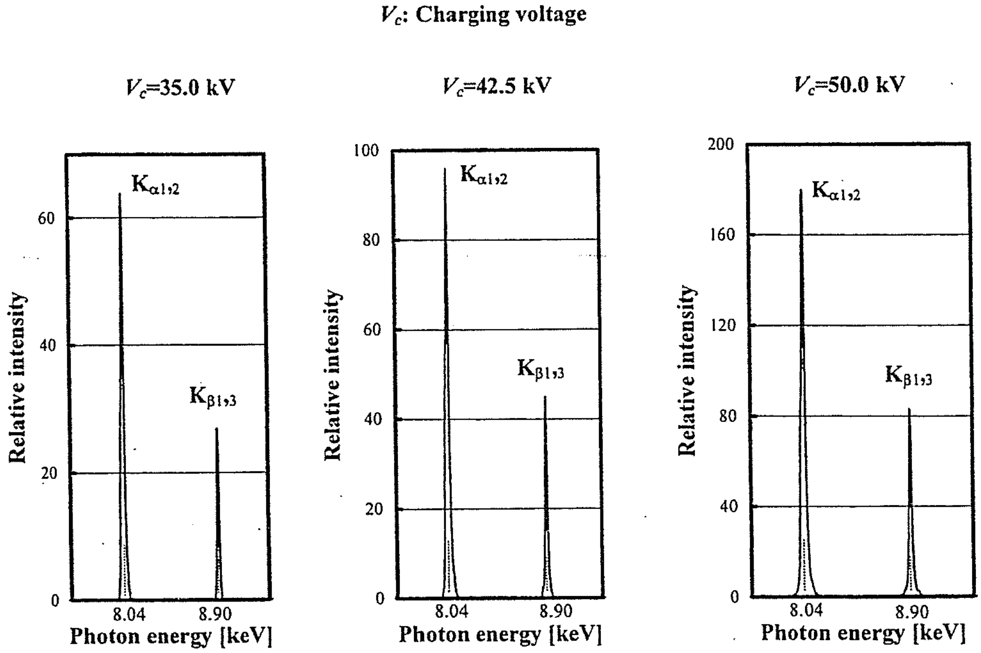

FIG. 6. X-ray spectra from copper plasma.

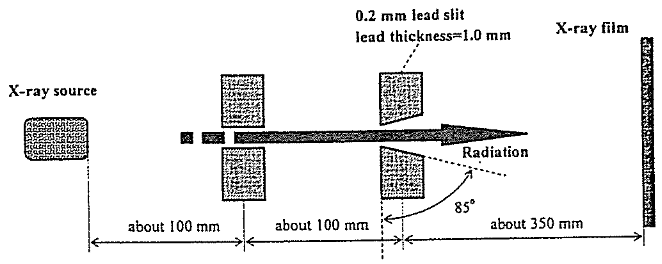

FIG. 7. Experimental setup for measuring x-ray divergence using two lead slits.

strahlung rays were hardly detected at all. The characteristic x-ray intensity substantially increased with corresponding increases in the charging voltage.

E. X-ray divergence by slits

In order to measure the difference in characteristics between x rays from a conventional tube and those from the plasma tube, we employed two lead slits in order to measure the divergence of the x rays (Fig. 7). As compared with x rays from a conventional tube with a tungsten target, the characteristic x rays from the linear plasma were diffused greatly after passing through the two slits (Fig. 8).

IV. RADIOGRAPHY

The plasma radiography was performed by the CR system (Konica Regius 150) without using a monochromatic filter, and the distance between the x-ray source and imaging plate was 1.2 m.

Figure 9 shows radiograms of 50 μm diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate, respectively, with a charging voltage of 50 kV. The image contrast of the wire around the pipe was higher than that of the rod, and the wires were almost completely visible. Next, the image of water spouted from an injector is shown in Fig. 10. This image was taken with a charging voltage of 50 kV, and an iodine-based contrast medium was added a little. Because the x-ray duration was about 1 μs, the stop-motion image of water was obtained. Figure 11 shows an angiogram of the external ear of a rabbit using iodine-based microspheres of 20 μm in diameter with a charging voltage of 45 kV, and fine blood vessels of about 50 μm are clearly visible.

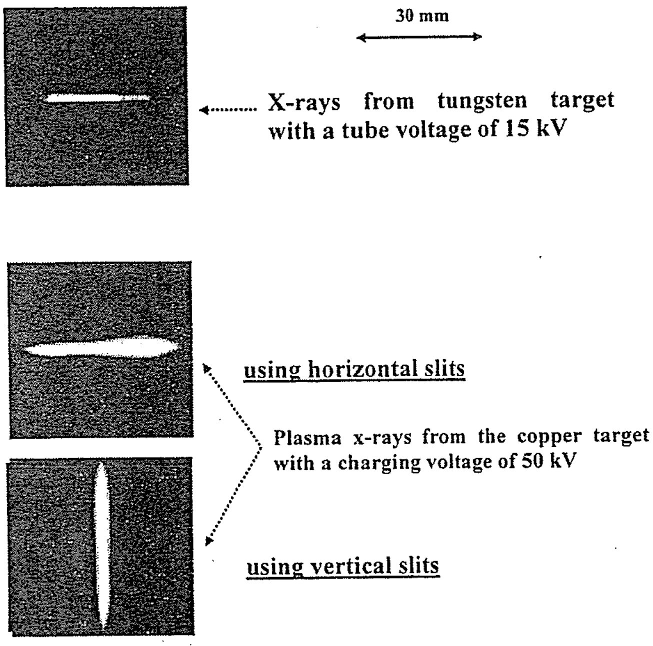

FIG. 8. X-ray divergence with two lead slits.

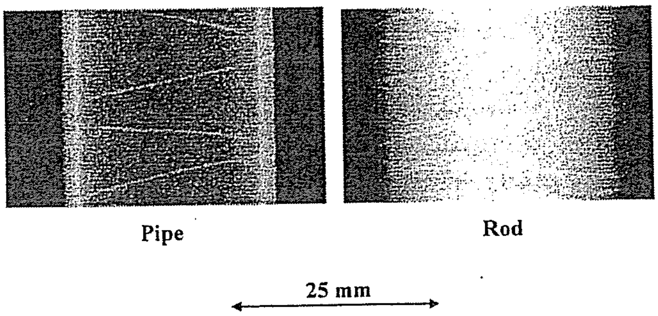

FIG. 9. Radiograms of 50 μm diameter tungsten wires coiled around a pipe and a rod made of polymethyl methacrylate, respectively, with a charging voltage of 50 kV.

V. DISCUSSION

Regarding the spectrum measurement, although we obtained quite intense and sharp K-series lines without bremsstrahlung x rays by forming a linear plasma x-ray source, we could not observe the difference between the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines. In addition, we confirmed the divergence of K-series characteristic x rays using two lead slits, and the maximum divergence angle was approximately 0.5°.

If we assume that the characteristic and bremsstrahlung x rays are signal and noise, respectively, the signal-to-noise ratio is higher than 1000:1, and this value is almost equal to those of soft x-ray lasers produced by the gas-discharge capillary.[21,22]

In this research, we obtained sufficient characteristic x-ray intensity per pulse for CR radiography without using a monochromatic filter, and the generator produced number of characteristic photons was approximately 1×10^{14} photons/cm^2 s at 1.0 m from the source. In addition, since the photon energy of characteristic x rays can be controlled by changing target elements, various quasi-

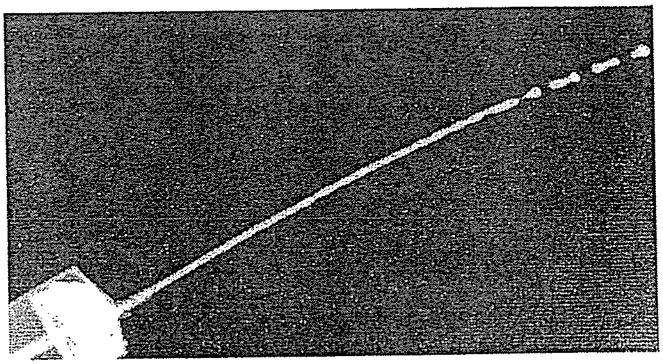

FIG. 10. Radiogram of water spouted from an injector with a charging voltage of 50 kV.

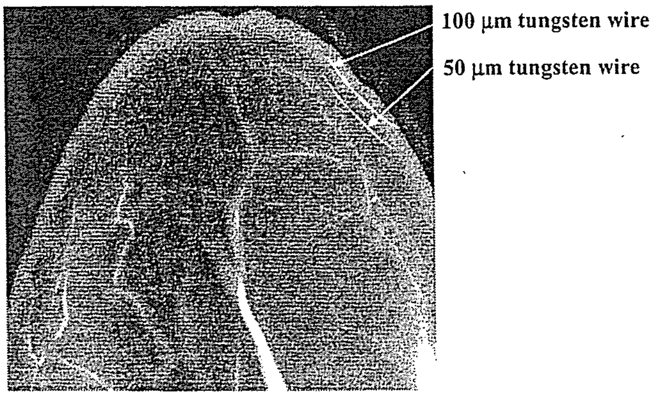

FIG. 11. Angiograms of the external ear of a rabbit with a charging voltage of 45 kV.

monochromatic high-speed radiographies, such as high-contrast microangiography[23] and parallel radiography[24] using an x-ray lens, will be possible.

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研 究 論 文

Irradiation of intense characteristic x-rays from weakly ionized linear molybdenum plasma

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Research Code No: 204.1
Key Words: flash x-ray, characteristic x-ray, quasi-monochromatic radiography, weakly ionized plasma, linear plasma

Abstract

In the plasma flash x-ray generator, a high-voltage main condenser of approximately 200 nF is charged up to 55 kV by a power supply, and electric charges in the condenser are discharged to an x-ray tube after triggering the cathode electrode. The flash x-rays are then produced. The x-ray tube is a demountable triode that is connected to a turbo molecular pump with a pressure of approximately 1 mPa. As electron flows from the cathode electrode are roughly converged to a rod molybdenum target of 2.0 mm in diameter by the electric field in the x-ray tube, weakly ionized linear plasma, which consists of molybdenum ions and electrons, forms by target evaporation. At a charging voltage of 55 kV, the maximum tube voltage was almost equal to the charging voltage of the main condenser, and the peak current was about 20 kA. When the

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charging voltage was increased, the linear plasma formed, and the K-series characteristic x-ray intensities increased. The K lines were quite sharp and intense, and hardly any bremsstrahlung rays were detected. The x-ray pulse widths were approximately 700 ns, and the time-integrated x-ray intensity had a value of approximately 35 μC/kg at 1.0 m from the x-ray source with a charging voltage of 50 kV.

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1. Introduction

Flash x-rays are a powerful tool for visualizing the inside of high-speed opaque objects, and the maximum photon energy has been increased to roughly 1 MeV in cases where Marx type high-voltage pulse generators are employed[1-3]. On the other hand, several different flash x-ray generators with energies of lower than 150 keV have been developed in order to perform soft radiographies with biomedical applications[4-12], and these generators have large capacity condensers in order to increase x-ray intensity by increasing electrostatic energy.

Recently, soft x-ray lasers have been produced by a gas-discharge capillary[13-16] to form linear plasma, in which laser intensity increases with corresponding increases in capillary length. However, it is quite difficult to increase the laser photon energy beyond 10 keV by light amplification by stimulated emission.

In light enhancement by spontaneous emission, characteristic x-rays are increased[17] in a thick solid target by conversion of bremsstrahlung x-rays into fluorescent x-rays without considering x-ray coherence. Then, by forming the weakly ionized linear plasma using a plate target[18,19], we confirmed irradiation of intense K-series characteristic x-rays from the plasma axial direction, and K-fluorescent yield in proportion to conversion efficiency increased with increases in atomic number.

In this paper, we describe a flash x-ray generator utilizing a rod-target radiation tube, which we used to perform a preliminary experiment for generating intense quasi-monochromatic x-rays by forming a linear molybdenum plasma cloud around a fine target.

2. Generator

2.1 High-voltage circuit

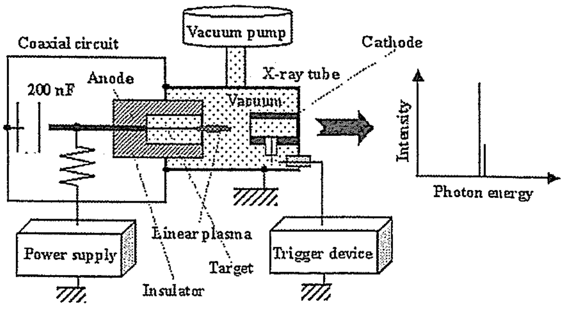

Fig. 1. Block diagram of the high-intensity plasma flash x-ray generator.

Figure 1 shows a block diagram of the high-intensity plasma flash x-ray generator. This generator consists of the following essential components: a high-voltage power supply, a high-voltage condenser with a capacity of approximately 200 nF, a turbo-molecular vacuum pump, a krytron pulse generator as a trigger device, and a flash x-ray tube. In this generator, a low-impedance transmission line is em-